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CENTER FOR INTELLIGENT ROBOTIC SYSTEMS FOR SPACE EXPLORATION (CIRSSE)
FIRST SEMI-ANNUAL RESEARCH REPORT
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I. INTRODUCTION

This is the first semi-annual report prepared to summarize the technical activities of the RPI's Center for Intelligent Robotic Systems for Space Exploration (CIRSSE) designated by NASA as one of the nine engineering centers of excellence granted in 1988.

The purpose of the Center is to develop an analytic theory for intelligent machines by fusing together concepts of AI, multisensor systems, multi-arm planning manipulation and control, and demonstrating its feasibility in a space or planetary environment by an appropriate demo project.

This report is divided into eight areas corresponding to the original proposed topics:

A. The Mathematical Theory of Intelligent Control
B. Multisensor Fusion
C. Task Planning and Integration
D. Multi-arm Manipulation
E. Adaptive and Learning Control
F. Reliability and Safety
G. Parallel Computation and Information Management
H. Moving Platform Demo Project

Each area contains summaries of all the individual research efforts developed in the area at CIRSSE.

A list of the research faculty students and technical staff is attached at the end along with a list of the appropriate journal and conference publications and CIRSSE reports.

The progress of acquisition and installation of the proposed computer network and the robotic and sensing hardware is included in the section of the demo project. Due to unavoidable delays in delivery of equipment, such progress is slow, but it is moving along within the anticipated time schedule which aims for a preliminary set up by the end of February 1989.

All other goals set in the proposal of the Center for this period have been met. The organization of the Center's administration is almost complete, with the Director, Administrative Assistant, Research Engineer and Executive Council in place. There are 31 students presently involved with the Center, 9 of which directly supported by the NASA grant and 22 supported by fellowships, university funds or resources. RPI recruitment support of new students especially U.S. citizens has been very successful.

There has been a considerable interaction with NASA Center and visits have been exchanged with Goddard and JPL. Interactions with the industrial group has been initiated and there were already three visits at our facility.

An open-house for NASA and industry people is planned for March 7-8, 1989, and a NASA day is planned for the IEEE Symposium on Intelligent Controls, which will take place in Albany, New York, in cooperation with RPI in September 1989.

Two small grants have been received from the RPI Center for Advanced Technology of the State of New York for Technology Transfer.

I would like to thank all the contributors of this report for their efforts and also Steve Hartman of NASA Headquarters for his continuing assistance in developing the Center in its infancy.

George Saridis
Director of
NASA Center for Intelligent Robotic Systems for Space Exploration

II. STATUS REPORTS

A. THE MATHEMATICAL THEORY OF INTELLIGENT CONTROL

1. A Coordination Model for Intelligent Machines

G.N. Saridis and F. Wang

The structure of Intelligent Machines is defined by G.N. Saridis to be the structure of Hierarchically Intelligent Control System, composed of three levels hierarchically ordered according to the principle of *Increasing Precision with Decreasing Intelligence (IPDI)* namely: the **Organization Level**, *performing general information processing in association with a long-term memory; the* **Coordination Level**, *dealing with specific information processing tasks with a short-term memory;* and the **Execution Level** which *performs the execution of various tasks through hardware using feedback control methods* (Figure A.1). A mathematical theory for Intelligent Machines has been presented in a recent paper by G.N. Saridis and K. Valavanis (1988), where the mathematical formulation for the Organization Level was developed.

The Coordination Level of an Intelligent Machine is an intermediate structure serving as an interface between its Organization Level and Execution Level for dispatching organizational information to execution devices. Its objective is the actual formulation of the control problem associated with the most probable complete and compatible plan formulated by the Organization Level that will execute in real-time the requested Job. The purpose of this research is to develop an analytical model for the Coordination Level of Intelligent machines, which, with the mathematical formulation for the Organization Level and the well developed control theory, would complete a mathematical theory for Intelligent Machines. This control and communication mechanism for coordination will enable the establishment of the information structure which specifies the necessary precedence relationship for the relevant information processing in the Coordination Level, and the formulation of the information flow which characterizes the actual decision-making activities for the achievement of the coordination objective.

The framework of the Coordination Level investigated consists of a dispatcher, a set of coordinators. A formal model, called *coordination structure*, has been developed to describe analytically the coordination activities among the dispatcher and the

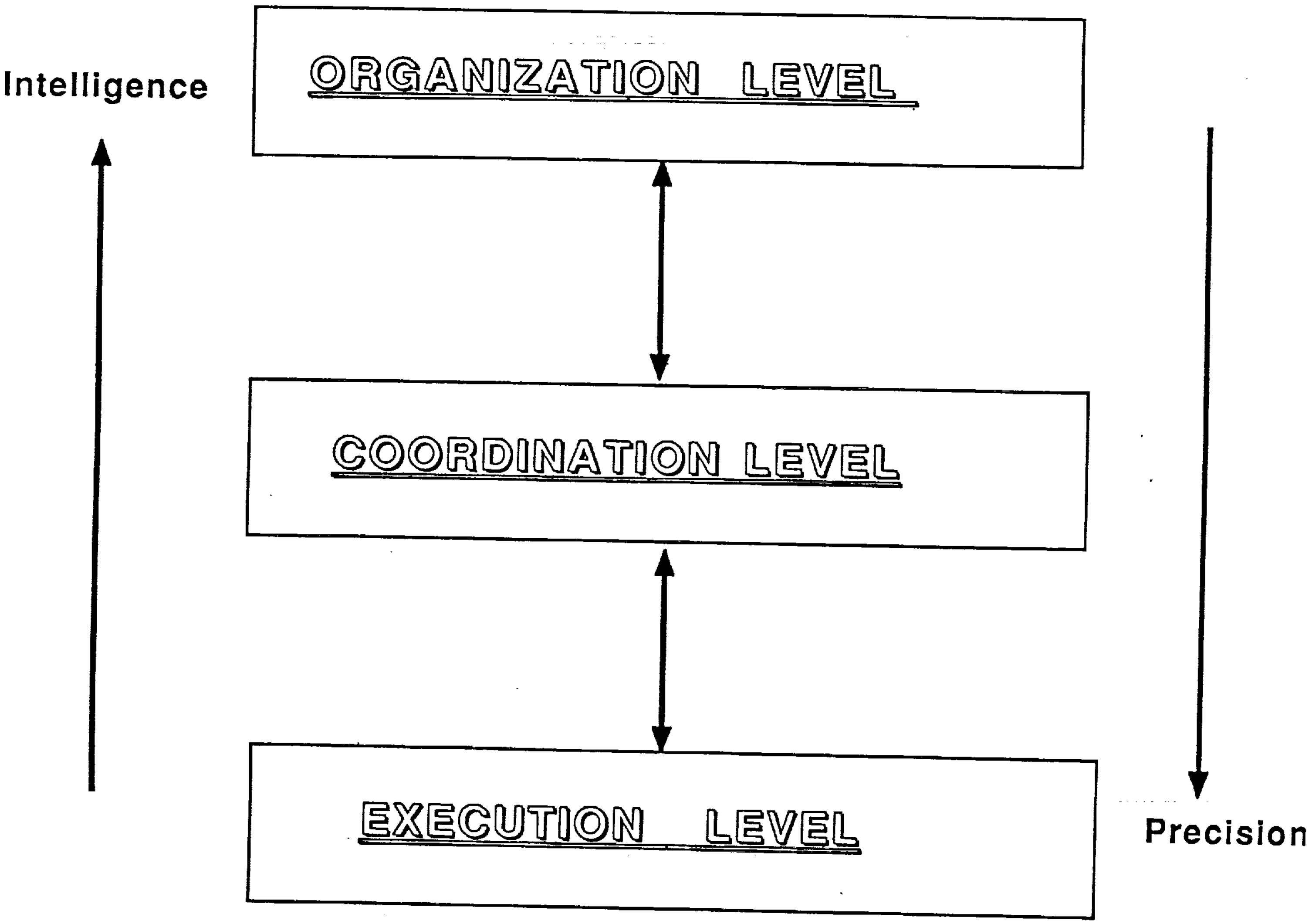

FIGURE A.1 The Structure of Intelligent Machines

coordinators of a Coordination Level. The use of the coordination structure enables us to:

a. Describe the language (or task plans) translation characteristics of the dispatcher and the coordinators.
b. Describe formally the individual process within the dispatcher and the coordinators, especially their concurrency and conflict.
c. Specify the cooperation and connection among the dispatcher and the coordinators.
d. Perform the process analysis such as deadlock-free, boundedness, etc., for the whole Coordination Level.
e. Provide a control and communication mechanism to be used for simulating and real-time, monitoring the tasks process in Coordination Level.

1 and 2 are accomplished by using *Petri net transducers* as the models for the dispatcher and the coordinators. A Petri net transducer is capable of performing the language translation and, like a petri net, can describe the parallel and conflict. The cooperation and connection among dispatchers and coordinators are specified by the connection points and the receiving and sending mappings of the coordination structure. 4 is realized within the context of Petri net theory, since various concepts and analysis methods have developed for Petri nets to deal with the deadlock, boundedness, and other process properties. The standard execution rule in Petri net theory provides the base for the construction of Petri net controllers, which can be used to control and monitor the coordination processes in the dispatcher and the coordinators in real-time.

2. <u>An Obstacle Avoidance Motion Organizer for an Intelligent Robot</u>
G.N. Saridis and C.H. Chung

In many path planning algorithms, attempts are made to optimize the path between *start* and the *goal* in terms of *Euclidean* distance. Since the moving object is shrunk to a point in the <u>Configuration Space</u>, <u>Findpath</u> can be formulated as a graph searching problem. This is known as the *VGraph Algorithm*.

Lozano-Perez points out the drawbacks of the <u>VGraph Algorithm</u>. The first drawback is related with rotation of a moving object. This drawback can be solved by using the *sliced projection method.* However, the *VGraph Algorithm* has serious drawbacks when the obstacles are three-dimensional. The *Extended VGraph Algorithm* is proposed to solve the drawbacks of the *VGraph Algorithm* by using the *Recursive Compensation Algorithm*. The *Recursive Compensation Algorithm* is proposed to find the collision-free shortest path in 3D and it is proved to guarantee the convergence to the shortest path in 3D and it is proved to guarantee the convergence to the shortest path in 3D without increasing the complexity of the *VGraph*.

B. MULTISENSOR FUSION

1. Multisensor Fusion

H. Kaufman and E. Simpson

The goal of this activity is the development of procedures for the detection of objects in and out of focus or blurred image sequences. To date, we have been developing software for adaptive model based filtering procedures that restore single frame images.

A user friendly interface is being developed for the SUN system configuration. Extension to sequences and the use of parallel computers will be considered as part of the activity for next year.

2. Minimal Representation Methods for Image Matching

A.C. Sanderson and R. Ravichandran

In this work we are extending the minimal representation criterion approach to image matching in order to provide more robust tools for model based matching of images in two and three dimensions. The minimal representation criterion provides an objective function for accommodating a variety of sources of error in noise image and models. Missing features, added points, noisy features, and attribute values, are accommodated by the approach. In the current work, the algorithms are being implemented on Sun Workstations with frame buffers for acquisition of images, and the current algorithms have been demonstrated in two dimensions. Extension of three dimensions is not straightforward due to the additional degrees of freedom required in the geometrical transformation. This extension is a principal topic for the continuing work.

3. CIVIL, The New C Language Version of the Vision Library

R.B. Kelley and M. Repko

CIVIL, the new C language version of the vision library was completed and installed by M. Repko. New features include the ability to handle different camera formats, implicit image parameter passing and automatic processing history generation.

4. Intelligent Robot Printed Circuit Card Identification and Insertion Tasks

R.B. Kelley, M. Repko and D. Sood

Two demonstrations dealing with intelligent robot printed circuit card identification and insertion tasks were implemented by M. Repko and D. Sood. The demonstrations employ overhead stereo vision, finger mounted IR light beam and proximity sensing, and wrist mounted force/torque sensing. The stereo vision is used to locate the cards in a supply area, classify the cards into the two types, and estimate individual robot gripper grasping sites. The IR light beam is used to reduce the grasp site estimation uncertainty by detecting the top edge and sides of the card to be grasped. The proximity sensors are used to locate the supply and insertion card cages in the absence of vision sensing. They are also used to monitor the region in the immediate vicinity of the robot fingers for obstacles. The wrist sensor is used to monitor the insertion process. The information from these sensors is combined using fuzzy logic to implement a fuzzy control of the process.

C. TASK PLANNING AND INTEGRATION

1. Tasking Planning Integration

A.C. Sanderson and R. Mathur

The work on task planning and integration has begun with a review of approaches to hierarchical control and planning architectures used with complex robotic systems. In particular, a review of the NBS style control architecture which prescribes a strict hierarchy of sensing, modeling, and control functions as well as the current approaches incorporated into the JPL Telerobot project, has led us to address several fundamental issues which need to be embodied in these systems.

- Representation - We are exploring an extension of our previous work on the AND/OR graph representation of assembly plans to a more generalized representation of manipulation tasks. This representation offers a natural partitioning and decomposition of the task in a manner which facilitates the reasoning about feasible plans.

- Reasoning - Reasoning in the AND/OR graph constitutes a search process in space of hypergraphs and in the extended AND/OR graph which is utilized in the representation of generalized manipulation functions. This search process must also accommodate the existence of hypergraph cycles and constraints on the utilization of resources.

- Evaluation Functions - The development of effective evaluation functions for the selection of feasible and desirable plans is fundamental to this approach. We are exploring the use of complexity measures and representation methods to provide evaluation tools for the selection of plans.

2. Multi-Arm Path Planning

S.J. Derby and S. Tocker

We have investigated several different approaches to multiple arm path planning/collision avoidance/manipulation based on the previous work of Pierre Dupont. His path planning algorithms, for a single seven jointed robot, were themselves efficient; but his use of Octrees as a solid modeler was a real bottle neck.

We have continued to work with the Dupont algorithm as the main thrust for multiple robots. The kinematics of two robot arms at any static location is rather trivial. It is the time varying locations and paths of two or more robots that is the research, and the method of representing these arms is the important tool.

The proper solid modeling software that efficiently allows for swept volume calculations appears to be a requirement for our research. Dupont previously found a better method of representing the robot's joint volumes, as per the current work of Lozano-Perez. A second viable approach is the use of the soon to be announced PRODEGEE software from XOX Corporation. Designed as a solid modeling kernel, user written routines can be written in C or LISP for access. The PRODEGEE software allows for four dimensional (using time as the fourth dimension) handling of solids. Swept volumes, and the position and time that they occur, are existing procedures. This could be extremely valuable to our effort. We have the first manual from XOX, and are awaiting the second and third in order to determine the usefulness and the efficiency of not "recreating the wheel".

We are investigating the best way to change from the MicroVAX/IBM PC-AT system to a SUN system to speed up the graphics. The combination of the Dupont algorithm, a faster solid modeler, and the SUN workstation should make for a very fast and powerful system.

D. MULTI-ARM MANIPULATION

1. Real-Time Navigation and Object Avoidance of Robot Manipulators

G.N. Saridis and K. Kyriakopoulos

The research efforts reported here are mainly focused on the definition and investigation of the subject of "ON-LINE collision prediction and avoidance in navigation and manipulation of robots in an environment of randomly nonstationary objects". The following issues have been stated and investigated:

a. Statement of the problem of collision avoidance in navigation as a **motion replanning** problem on the cartesian off-line preplanned trajectory.

b. Full investigation of fast collision detection techniques. The basic assumption made was that both the robot and the moving object(s) are described as convex hulls. The following issues have been the core investigation and are still under research:

- Performance in terms of computational complexity of the 1, and ∞ norms to represent the distance functions between convex hulls.
- Sensitivity investigation of the above norms for two reasons:
  - -- To obtain estimates of the reliability of the obtained minimum distance values
  - -- To find fast update strategies as the objects move in time.
- Norms 1,2 and are equivalent in R^n. What are their in-between bounds?

c. Definition of the on-line collision avoidance operational diagram and statement of the decision making problem as:
   - A search of a stable controller. That is, find a controller to assure that no collision is going to be performed, and
   - A search of an optimal controller, that except for stability guarantees performance in terms of user defined requirements.

   It is noted that these issues have just been stated and work is currently being performed.

d. Initial investigation of the uncertainty considerations. First the sensing uncertainty was encountered and the problem of transforming it through certain mappings was solved. Then the entropy formulation was selected. The issues concerning the uncertainty problem are:
   - Quantitative evaluation of the sensing uncertainty due to hardware limitations of the vision equipment.
   - Transformation of the above uncertainty to the world coordinate frame.
   - Sensitivity of the numerical evaluation of the minimum distance to uncertain information.
   - Statement of the problem to on-line avoid objects either as a disturbance rejection problem, or a stochastic optimal control problem.

2. <u>On the Cartesian Control of Orientation and Force for Robotic Manipulators</u>
   G.N. Saridis and S. Murphy

The problem of controlling the orientation of a manipulator end-effort when the dynamic equations of the manipulator are expressed directly in Cartesian space is examined. The model of manipulator orientation is developed through a common Cartesian control scheme and the basic nonlinearities of Cartesian orientation are shown. Three methods of regulating orientation are investigated, and the results show the conflict between performance and calculation complexity. None of the rotational regulators performs adequately over the entire space of orientations. The control of orientation provides information into the development and interpretation of the manipulator Jacobian and the impact on force control in Cartesian space. The work shows the need for an orientation regulator that does not artificially limit the range of manipulator orientations and has a reasonable calculation cost.

3. <u>Performance and Evaluation of Control Architectures Using Petri Nets</u>
A.A. Desrochers and J. Robinson

In the Petri Net work, J. Robinson has been closely following the performance evaluation work that previous investigators were doing. She has also familiarized herself with the software we have obtained for Petri Net Analysis: DEEP from Duke University, Great SPN from the University of Torino, and GTPNA from the University of Wisconsin. All of these packages are up and running on the VAX 11/750 and/or the SUNstation.

4. <u>Multiple-Arm Control</u>
J.T. Wen

Under the assumption of rigid grasping, globally stable tracking and force controllers have been developed for multiple arms holding a common rigid object. For the tracking control, an energy motivated Lyapunov function framework is found suitable for the stability analysis. At the present, the class of desired trajectories is limited to those converging to a steady state. The tracking of the class of desired trajectories is limited to those converging to a steady state. The tracking of more general classes of trajectories (for example, periodic motion) is under investigation. For the internal force control, if force/torque at each contact point can be measured, high performance setpoint force control can be achieved without much model information (only arm Jacobians are needed).

An area that is currently under active investigation is the generalization of our results in the rigid grasp case to the mutliple-degree-of-freedom contacts (for example: rolling, sliding, point pivot, soft finger).

E. ADAPTIVE AND LEARNING CONTROL

1. <u>Adaptive and Learning Control</u>
H. Kaufman and G. Neat

The goal of this work is to develop an expert, hierarchical control scheme that adapts its structure in accordance with a broad range of plant variation and knowledge about the plant. The coarsest control, provided by a fuzzy controller, moves the state of model adaptive control procedure provides the next level of control by forcing the plant's response to exist within a predetermined allowable range of specifications. The finest control is determined by a model reference adaptive controller that causes the plant to follow a desired reference model. The heuristics used to determine switching between different controllers is orchestrated by an expert system that bases its decisions on plant responses and controller parameter values.

Applications to representative robotic models will be considered over the next year.

2. Adaptive Expert Control

L.K. Lauderbaugh and G. Sullivan

In the application of adaptive control structures to the space environment, paper behavior of the controller must be guaranteed in both steady state and transient modes of operation. Experience with earthbound adaptive controllers has shown that considerable "tweaking" of an adaptive controller must be done to obtain good performance. Problem such as measurement noise and insufficient excitation of the plant can actually cause instability if no "safety nets" have been added to the adaptive controller. In space, where human operators may be unavailable for large period of time, autonomy of the adaptive controller is of primary importance. Work on a two level controller is presented that uses an expert system to act as a safety net for the adaptive controller, monitoring the status of the adaptive controllers and applying extra algorithms and adjustments to the adaptive controller as they are needed to ensure good performance.

3. Overview of the System and Current Work

L.K. Lauderbaugh

Adaptive control is presently the best way to control systems which have dynamics that are not well modeled or where the dynamics are time varying. Adaptive controllers use real time estimates of the plant's dynamics, based on input/output data from the plant to adjust the control law being used. As long as certain preconditions are met, changes in the dynamics of the plant can be followed and good performance is maintained. In practice, it is not always possible to satisfy all of the conditions for proper tracking of the plant's dynamics and poor performance results. Most of the problems that occur in implementations of adaptive control may be attributed to four problem areas listed as follows:

a. Insufficient Excitation
b. Noise Problems
c. Numerical Errors
d. Model Order Selection Problems

To deal with these problems in any given application of an adaptive controller, the designer must include extra heuristics and algorithms with the basic adaptive control algorithm. The process of deciding which algorithms and heuristics are warranted requires experience and constitutes what is a largely undocumented "art" of adaptive control implementation.

The purpose of the A/E controller is to automate the "art" of adaptive controller implementation through the use of expert systems technology. In the A/E controller an expert system is used to monitor an adaptive controller and administer auxiliary procedures to the adaptive controller as they are needed. The A/E controller consists of four main phases: an adaptive controller, a signal-to-symbol interface, a symbol-to-procedure interface, and the expert system module. The signal-to-symbol interface gathers raw data from the adaptive controller over a constant time period called the expert system sampling interval, and calculates a set of fourteen "feature variables" that describe the state of the adaptive controller. At the end of the expert system sampling interval, the signal-to-symbol interface converts the feature variables into symbols by comparing the value of each feature variable to thresholds associated with given symbolic phrases. After feature variables are converted into symbolic representations, the expert system module polls the signal-to-symbol interface and receives a symbolic description of the adaptive controller. Using information from it's knowledge base along with the symbolic description of the adaptive controller, the expert system module formulates a schedule containing the names of procedures that will be used to enhance the performance of the adaptive controller. The last step in the A/E controller cycle is performed by the symbol-to-procedures interface, which takes the names of the procedures listed on the schedule, and attaches the corresponding procedures to the adaptive control algorithms.

To begin development of the A/E controller, a prototype was constructed and feasibility of the concept was demonstrated. The prototype used a backward chaining type inference engine to retrieve diagnostic information on adaptive control from a rulesbase which contained twenty rules. Scheduling was simplistic, and proceeded by going through a list of possible algorithms that could be applied, and querying the expert system to see if a given algorithm should be used or not. The prototype was fun on an IBM PC/AT, with LISP being used for all inferencing operations and FORTRAN for all numerical routines. Despite the fact that the prototype is fairly simple, we found that expert supervision of the adaptive control process did improve the performance of a time varying plant in simulation.

In the previous sections, the concept of the A/E controller has been reviewed and as the prototype suggests, the A/E controller will be able to make adaptive control more reliable. In this section, ongoing work is discussed. The work presently being conducted can be divided into three categories:

a.. Upgrading the expert system facility
b. Finalization and coding of scheduling algorithms
c. Development of additional algorithms to aid adaptive controller.

In our early experiments with prototype, the inference engine used only "logical constants" to do inferencing with (i.e., no variables were used). This proved to be a limitation to the style of rules that could be written and forced a high degree of redundancy in the information transferred from the signal-to-symbol interface, to the expert system module. In addition, none of the standard relations, "not", "and", "or", "greater-than" and "less-than", could be used. Again, redundancy and inefficiency is the result. For these reasons one of the tasks begun this semester was to construct a formal grammar for the knowledge used by the A/E controller, with the associated parsing and inferencing algorithms.

As noted earlier, the scheduling method of the A/E prototype was fairly simple. Although the prototype was able to assess the situation at any given time, it was unable to appraise the success or failures of it's actions, and contained no knowledge about how to handle conflicts in schedules or interactions between different algorithms on the schedule. Over the past semester, the mechanisms by which the final version of the A/E controller plans it's schedules have been defined and many of the scheduling utility functions have been coded. The major task left here is to write a function that generates constraints for the different procedures that may be used at a given time and, then finds the optimum schedule (i.e., the schedule that satisfies all constraints in a minimum total time).

The last item mentioned above the development of more algorithms to aid the performance of the adaptive controller. Presently, we are looking at algorithms to detect a change in the order of the plant model and correct the model order if a change occurs. In addition, the problems of identifiability in closed loop has been examined in detail in order to come up with rules for selecting control laws that will allow accurate system identification.

F. RELIABILITY AND SAFETY

1. Robot Safety Study

L.K. Lauderbaugh and D. Montgomery

Terrestrial operation of autonomous robots, with their unfamiliar and often unpredictable movements and extended range of motion, has resulted in the creation of new safety hazards to add to the long list of risks associated with the operation of traditional industrial machines. To these safety hazards we will soon add hazards associated with the employment of robots in space operations. A major goal of the research conducted at Rensselaer from September 1987 through December 1988 was to satisfy the need for structure in the study of robot safety, and apply this structure to the study of space robot safety.

A review of studies of terrestrial robot fatalities and accidents and of domestic and international robot safety standards shows the need for identifying hazards and assessing risks associated with each mode of robot system operation. Requirements for safeguarding personnel from injury and equipment from damage can be identified and organized by viewing robot operation in the proposed matrix safety frame. By performing a hazard assessment and risk analysis for each cube of volume in the matrix safety frame, we were able to identify safeguarding requirements. The result of this modular approach to safeguarding is a structured collection of recommendations for the safe design and operation of robots and robot systems. After modifying, adding and deleting recommendations as required for operation in the space environment, the recommendations were incorporated into a hazard identification checklist, a qualitative safety tool for robot systems designers and robot users. Entries in this checklist fill discrete volumes of the matrix safety frame. The contents of the checklist are categorized as follows:

- Environment
- Control System
- Mechanical Design
- Memory Storage
- Standard Engineering Design Practices
- Gripper Design
- Robot Location
- Electrical Design
- System Layout
- Power Supply
- Robot Operations
- Emergency Stop
- Astronaut Training/Certification
- Presence Detecting

The checklist is not all inclusive, but instead provides a starting point from which to extend further developments.

A matrix safety frame for safeguarding robot system is multi-dimensional. The three-dimensional matrix safety frame shown in Figure F.1 was proposed as a means of providing structure to the otherwise unstructured mass of safeguarding information.

The modular nature of safeguarding using a matrix safety frame can be seen through an examination of Figure F.2. Through inspection we can count a total of 4 x 3 x 2 = 24 cubes in the three dimensional frame. These are the cubes of volume which are isolated when using the hazard identification checklist to assess safeguarding requirements. The example displayed in the figure is intrinsic safety in the operation (dimension S) of a space robot for aberrant operation under a subsystems failure (dimension O) during programming (teaching) (dimension M). We see that this example fills one cube of volume in the complete three-dimensional matrix safety frame.

It is easy to see that a thorough hazard assessment using a matrix safety frame could be exhaustive and potentially prohibitive given time, money or other constraints, thus a quantitative or qualitative injury or damage potential could be assigned to aid in prioritization of individual hazard assessments. This prioritization could be based on an assigned level of severity of the possible human injury or equipment damage. Individual volumes of the matrix safety frame with high severity ratings could then be assessed first, and the implementation of required safeguards be given higher priority. This is one area of future research.

The current state-of-the-art in ensuring the safety of terrestrial robots and robot systems is checklists, flow charts and fault-tree analysis. The present research provides the groundwork for advancing the state-of-the-art of robot safety, specifically for robots operating in space. We will continue to develop quantitative measures by viewing robot safety in the proposed matrix frame.

Much work remains to be done to determine the feasibility of expanding the present volume of information to develop an expert system for safe design and operation of space robots and robot systems (see the next section). Once feasibility has been assured, the actual development of a frames and/or rules based expert system will require the collaboration of a team of personnel from various engineering disciplines. The goal of having the expert knowledge of senior robot system designers, operators and maintenance personnel systematically organized for interactive reference by newer, less experienced robot designers, operators and maintenance personnel has been set. This continuing research aims to realize that goal.

2. Robot "Safety Controller"

L.K. Lauderbaugh and V. Ree

The science of decision theory has been developed considerably to the point that its principles can be automated. However, even though computation times to arrive at decisions are vastly shorter than that required by a human, such computation times are finite. If a problem is significantly complex, the times to arrive at a decision may be considerable.

In critical situations, the results of an incorrect decision may be disastrous. Therefore, it is even more important that a "correct" decision is made. Weighing additional factors and checking the results become part of the decision process. This, expectedly, would increase the computation time. Unfortunately, many critical situations are an emergency which places a time constraint on any decision-making process.

The problem at hand is this. In general, how can we adjust the decision-making process such that an automated system will, given time constraint (which the system itself might have to estimate), arrive at the "correct" decision. In addition, the system must also be able to implement any solution that decision requires in that time constraint.

Specifically, we are looking at the problem of developing a "safety controller" to an automated system such as NASA's Flight Telerobotic Servicer (FTS). The purpose of the controller is to monitor the actions of the system and its environment for possible hazardous situations which might arise and take corrective action.

Currently, research falls into two categories:

a. Developing a decision theory for safety problems. This involves clarifying definitions of safety, risk, etc., so that the system will be able to execute any control actions of any "safety-related signals". In additions, we are developing techniques to measure and analyze these quantities in a similar fashion to that of reliability theory.

b. Developing the appropriate architecture of an automated system so as to optimize the safety control process in conjunction with the system's primary functions. Besides architecture, we need to work on the analysis of safety problem solving from a computational point-of-view, specifically identifying and estimating safety problems and the ability of the system to resolve such problems. This is connected with safety decision theory mentioned above.

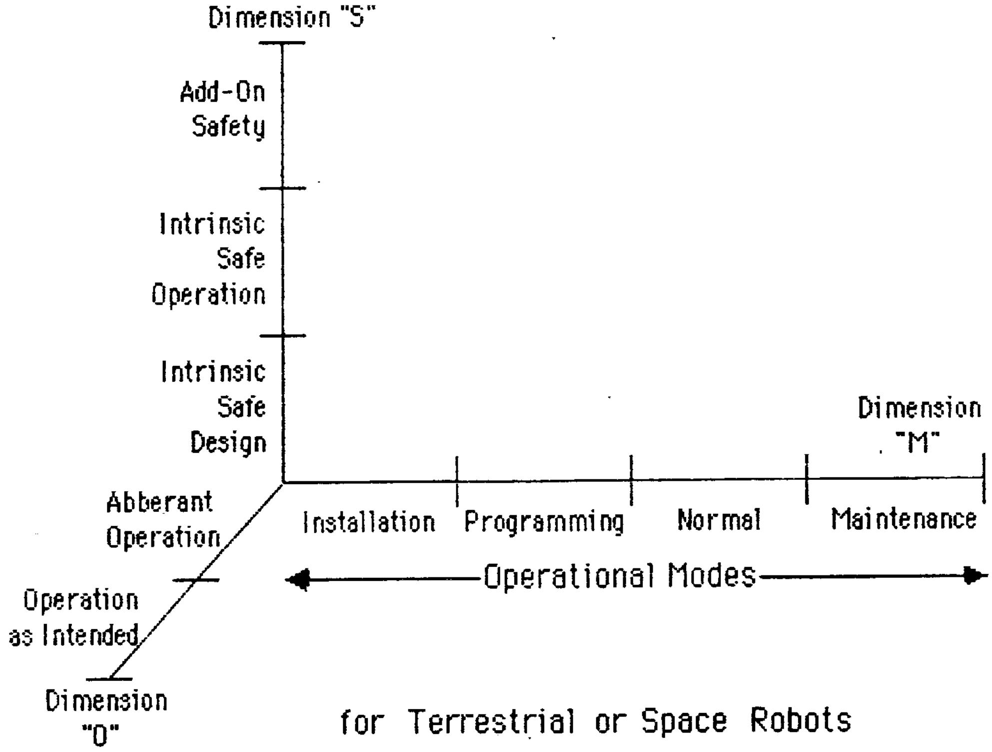

FIGURE F.1 Matrix Safety Frame

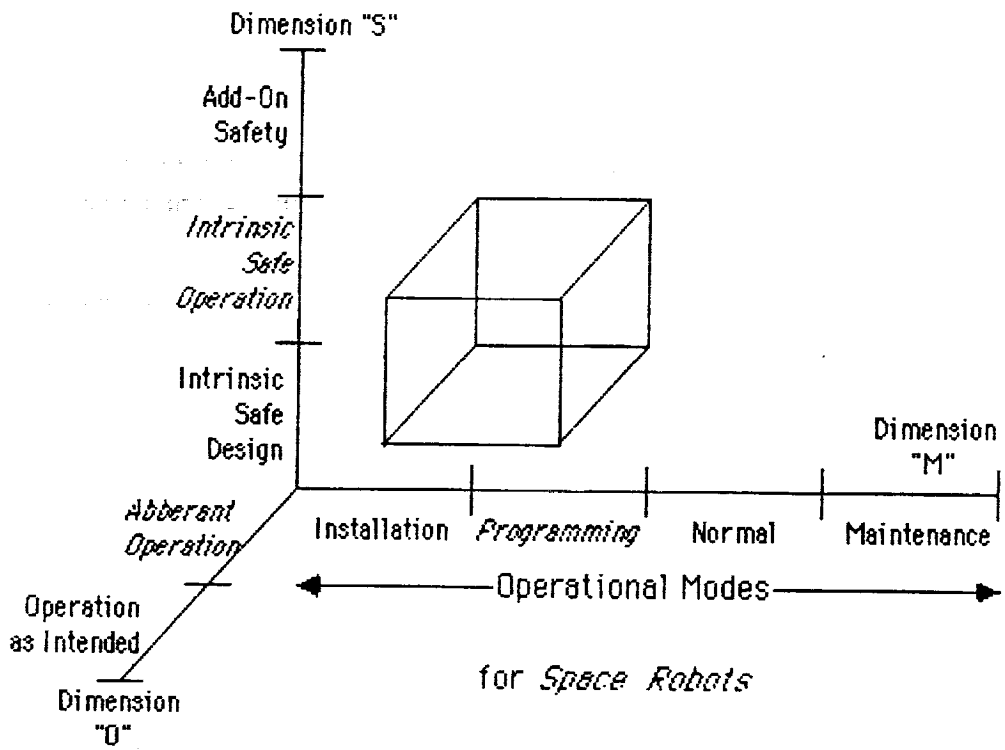

FIGURE F.2 Example: Space Robot Matrix Safety Frame

G. PARALLEL COMPUTATION AND INFORMATION MANAGEMENT

1. Information Management

L.A. Gerhardt and F. Miller

Given the three types of information management: Data, Imagery and Voice, the emphasis of this research is on the first two. A preliminary study was done of the principle investigators on the grant to determine their initial thoughts and needs with respect to distribution of databases, distribution of functions, distribution of sensors and resulting LAN requirements. Other considerations currently continuing under investigation are sensor processing at the focal plane versus centralized processing. The trade-off between speed and bandwidth are also being studied as well as the ability of the information system to dynamically reconfigure for purposes of graceful degradation versus catastrophic failure.

Architecturally we are considering the needs for parallel processing and the opportunity for Petri Nets as an integrated approach to control, databases and networking within the system.

Finally, the information needs as a function of the degree of autonomy, that is fully autonomous operation, telepresence, or teleoperation will also be considered.

This initial survey and literature search, and some comparative analysis have been started during this period on the issues above. Most of all, this area has been scoped out and will be pursued in more depth in the next year.

2. 3-Dimensional Sensing

L.A. Gerhardt and F. Miller

The area of specific interest that we have identified is the analysis, development and application of 3-Dimensional Sensing in the space environment. In particular, the issue of Image Motion Compensation for a 3-dimensional sensing system will be considered, and the resulting implications on system information requirements.

This is to be compared to the work of Professor H. Kaufman, which is considering only 2-dimensional imagery and object motion within an image and image deblurring.

Here we are considering 3-dimensional images and specifically that the image may be moving due to instabilities of the platform on which the overall system (in whole or in part) is mounted.

An initial literature search has began. We have considered various system architectures including a single camera with associated structured light as well as multiple camera configurations with and without structured light. Using the existing RPI 3-dimensional vision system as a reference, we have begun to consider the system hardware architecture. Specifically we have looked at the optimum camera placement and the number of cameras required to minimize the effect of vibrational characteristics, and we have begun a statistical analysis of estimating the ranging error of different system configurations as a function of camera geometry. We also plan to look at the analysis of the system as a function of the degree of knowledge of the disturbance as well as that of the object being viewed (complete/incomplete model description), using aspects of AI (knowledge based).

We have also given consideration to the system requirements with respect to the demonstration platform and our needs for vibrational stimulus as well as "real estate" needed on the platform.

During the course of the first of the coming year, we expect to begin to do some software development with respect to a literature search and independent development support the 3-dimensional vision system architecture. We anticipate formulating the hardware system configuration and complete preliminary statistical analysis with respect to geometric considerations and specification of test disturbances needed to perform proper evaluations.

Needs for information management will be solidified, particularly with respect to the bandwidth speed trade-off and graceful degradation in the event of system failure. Also to be emphasized will be the need for distributed versus centralized information with respect to databases and control as a function of the degree of autonomy to be used.

H. MOVING PLATFORM DEMO PROJECT

The Demo project will provide CIRSSE with a facility where experimentation and demonstration of the various research projects can take place. This project will be divided into four major categories: Computer Systems, Real-Time Control System, Vision Systems and Mobile Platform. Each of these are discussed in detail. A CIRSSE NASA Lab configuration diagram is included at the end of this section as Figure H.4.

1. Computer System

K. Walter

The Demo project will have full access to all of the facilities listed below.

- SUN 4/260
  - -- File/Compute Server to CIRSSE Local Network
  - -- Gateway to RPI Campus Network
- SUN 3/260
  - -- Host to 3D Vision System
- SUN 3/150
  - -- Host to Real-Time Control System
- SUN 3/60
  - -- Program Development Workstation
- VAX 11/750
  - -- Terminal Server
  - -- Host for Existing Applications Software

All of these systems are currently in place with the exception of the SUN 3/260 system. Delivery of this system it projected for the first week of February 1989. All CIRSSE computer systems are networked and communicate via TCP/IP ethernet. ARPANET access is available through an RPI campus gateway machine.

2. Real-Time Control System

K. Walter and F. Miller

As a minimum, the Real-Time Control System consists of the hardware and software necessary to effect real-time (RT) control of both PUMA arms. The CIRSSE RT control system is being designed to meet the following goals:

- Minimization of hardware/software development time.
- Expandable, multi-processor, VME bus system.
- Closely coupled to SUN host system via VME connection.

Using a VME bus system gives us a wide range of "off-the-shelf" products that can be used to configure a system. RT software selection, however, has taken longer than anticipated. Two packages were investigated, CONDOR from Sarcos Research Corporation, which was developed for the Utah-M.I.T. Hand and VxWorks from Wind River Systems, Inc., a commercially available UNIX environment. VxWorks was selected after evaluating feedback from users of both packages, including personnel at JPL who rated VxWorks very highly as a research tool.

We also want to provide a high level software interface to the RT control system, and RCCL will be used to do this. The version of RCCL that we are currently using on the VAX, is not suitable due to its age and undocumented coding. The current version available from McGill University supports two arms, but only runs on SPARC architecture SUN's running SunOS release 3.X. We will order this product when it is available for SunOS release 4.X.

Graduate research students are working on the hardware and software that will be needed to communicate between the RT control system and the PUMA's PDP-11 controllers. When all of the RT system components are available, the robot controller communications support will already be in place.

The following items must be ordered to complete the RT control system:

- VxWorks Real-Time UNIX Software
- Additional Hardware (to enable running VxWorks)

- A/D, Serial I/O Hardware
- RCCL, when available for SunOS 4.X.

Mr. F. Miller's responsibilities include putting in place communications software needed to connect the SUN robot controller and its loosely coupled parallel processors with the PDP-11s which control the labs PUMA arms. The goal of this package is to provide a standard robot arm interface mechanism so that the control algorithms which will be running on the parallel processors might be developed on any of the available host processors. Communications protocol has been developed and shown to work in a limited fashion between the labs current VAX based host computer and the PDP-11s. Further effort is required to fully debug the current software and to evolve it into the robust and failsafe package the demo project requires.

3. Vision Systems

K. Walter

Currently CIRSSE has a MATROX MVP-SUN vision system which will be hosted by a SUN3/260 with a TAAC-1 applications accelerator. This system can support up to four monochrome cameras or one color camera at various video standards. When the SUN3/260 is delivered, this system will be installed.

High performance vision systems, possibly incorporating massively parallel SIMD architectures are also being considered. The research requirements have to be further defined before proceeding in this area.

4. Mobile Platform

S. Murphy

4.1 Platform Goals. The initial goals for the platform were given as a general set of desired parameters. If possible, the mobile platform was to have 6 degree-of-freedom, accommodate two robots on a common base; or two robots on separate bases, and cost in the neighborhood of $70,000. A conceptual drawing showing the robots on a common base is shown in Figure H.1.

In the initial stages of investigation, it became clear that more detailed specifications for the platform were necessary and trial specifications were developed.

These specifications were calculated using the speed and accuracy of the PUMA manipulators as guidelines. The goal of the platform specifications was to give a system equally as repeatable and as fast as the end effect of the PUMA.

Unfortunately, in the process of investigating mobile platform proposals, none were found that could meet these specifications and maintain cost limits.

4.2 Unfeasible Proposals. The following proposals were deemed unusable due to their extreme cost, or incompatibility with the desired motion of the platform. They are presented here as examples of the wide range of options available for the mobile platform.

- 6 DOF Stewart Platform. A large, 6 DOF platform is manufactured by Link Flight Simulator for $500,000. While this platform exceeded all cost, space, and motion specifications it was the only full 6 DOF platform found this study.

- 4 DOF Platform. A smaller platform, more in line with the goals of the platform project is also available from Link Flight Simulator. Having only 4 degrees of motion and a cost of $150,000, the platform s hydraulic and will not be available immediately.

- Vibration Table. A table for providing high acceleration for the robot manipulators is manufactured by Schenk-Pegasus Corporation. Available for $500,000, this platform could simulate the motion for also any space or ground based vehicle in 6 DOF. Since the table is designed primarily for vibration studies, the excursion of the platform is small.

These proposals were valuable in that they showed the impossibility of meeting the goals for the CIRSSE platform within the cost requirements. It became clear that compromises would need to be made regarding the number of degrees of freedom, and the rate and control of motion.

4.3 Active Proposals. The following proposals are active in the sense that they are still under investigation as feasible solutions for the CIRSSE mobile platform.

- Wheeled Platform. Figure H.2 shows a conceptual drawing of how wheeled platforms could be used in the CIRSSE project. These platforms would provide X, Y, and rotational motion for the robot manipulators. They have the advantage of lower cost and a wide range of possible applications. Their disadvantages include difficulty of accurate motion and global positioning as well as overall stability under the robot mass and cabling problems. The computer interface capabilities vary with cost and complexity.

- Tilt Tables. Rotary, tilting tables are available from a number of manufacturers. These tables have up to 3 degrees of rotational freedom and some may accommodate the load of two robot manipulators. These tables would provide a quick method for allowing rotational positioning of the robots at an approximate cost of $50k (2 robots). Such tables allow up to a tilt, which could place the robots in a horizontal position. The disadvantages of the tilt tables are that they rotate slowly because of their accuracy for machining operations and weigh between 1000 to 2000 lbs. The interface requirements for these tables have not been completely investigated.

- Custom Approach. A third approach is to assemble a 3-4 degree-of-freedom platform with commercially available actuators and controllers. A number of companies, such as Aerotech Inc., provide motion control products which may be used to create the desired platform motion and control. This approach has the advantage of allowing complete customization of the motion and the computer interface. The disadvantage of such an approach lies in the amount of time and knowledge required to purchase, assemble, and debug such a system.

4.3 Conclusion. The results of this work show the large range of possibilities available for construction of the CIRSSE mobile platform. Because of the cost, space, and interface constraints on the project, not all of the platform goals may be met. The specifications for the platform will need to be adjusted to accommodate the compromises. In order to effect these compromises, it is felt that a clearer goal for the use of the platform should be established.

As a basis for discussion and for use with company-product specifications, the following proposal for the CIRSSE mobile platform is given.

- Mobile Platform Specifications. Figure H.3 shows the concept of a suggested mobile platform structure for the NASA CIRSSE. The system would consist of two bases each with 2 rotational degrees of freedom. One degree of linear motion will be used to control the distance between the robots. It was noted during conversations with JPL, that a larger interest was placed in having the robots mechanically separable. Table H.2 gives the most desired excursions and velocities for the motion. These numbers represent the peak performance requirements. It is expected that compromises in these specifications will need to be made in order to meet the total cost limit.

- Computer Interface. The motion of each base should be controllable through a high-speed parallel or serial communications line.The optimal computer interface should have two modes of operation.The first mode would allow a control computer (provided in the CIRSSE) to send motor currents to each rotational and translational actuator and to read the position, velocity of each motion. The time required for reading positions and sending new currents should be under 2ms. The second mode of operation would be more like a CNC system where velocity profiles and positions would be sent over the communications line and the purchased motor control system would provide the appropriate servoing to the desired position.

- Additional Degrees of Freedom. A desirable feature for the system would be the capability to add more degrees of freedom as the need and funding arose. First steps could involve adding linear motion in the X,Y directions.

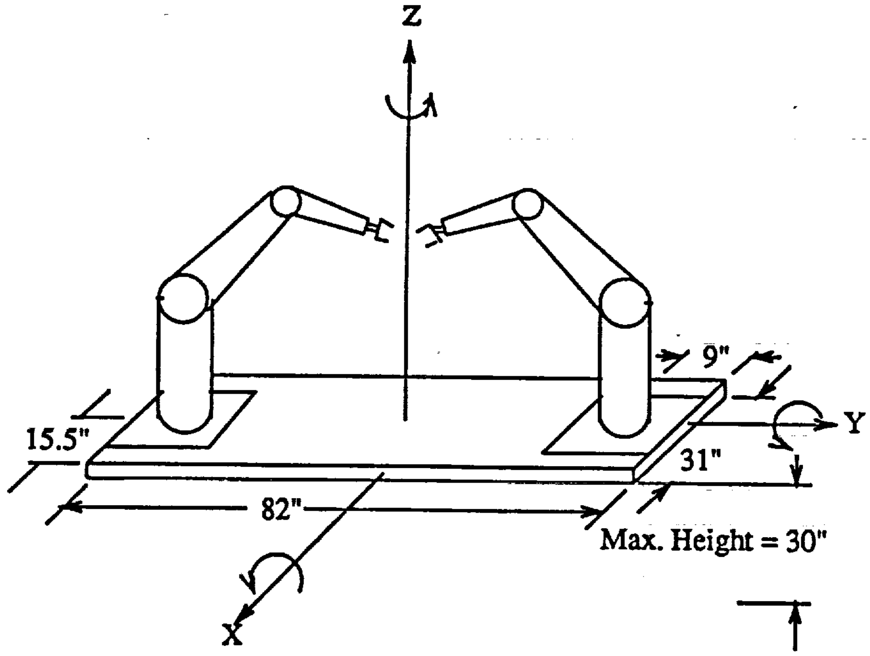

FIGURE H.1 Common Base 6 DOF Mobile Platform

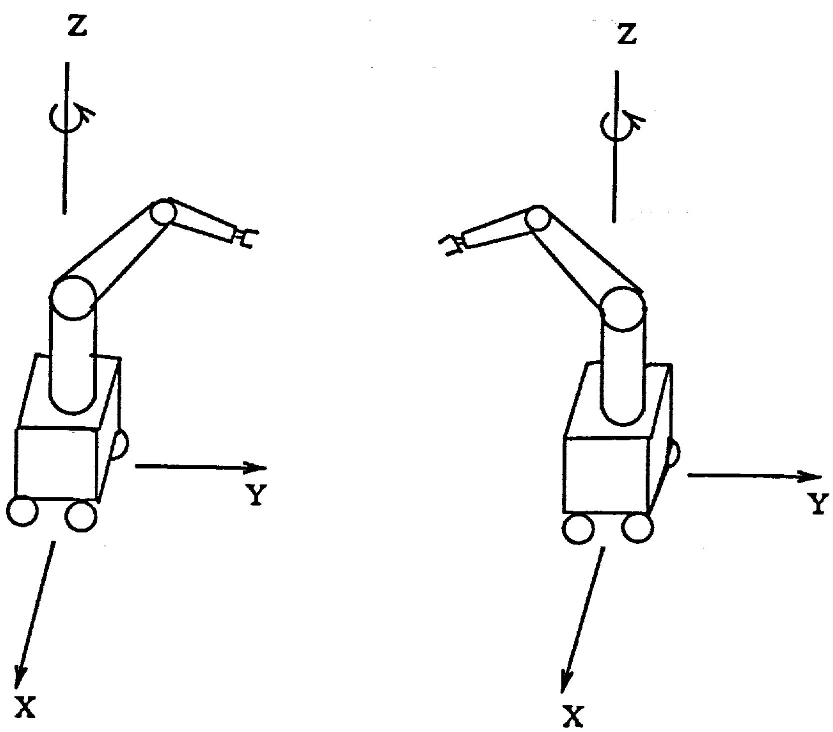

FIGURE H.2 Wheeled Mobile Platform

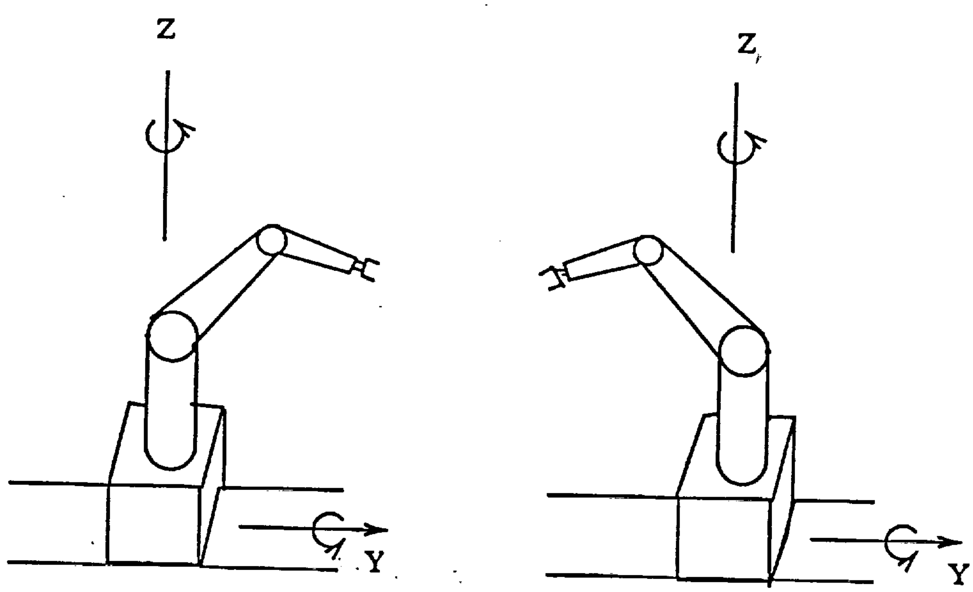

FIGURE H.3 Proposed CIRSSE Mobile Platform Structure

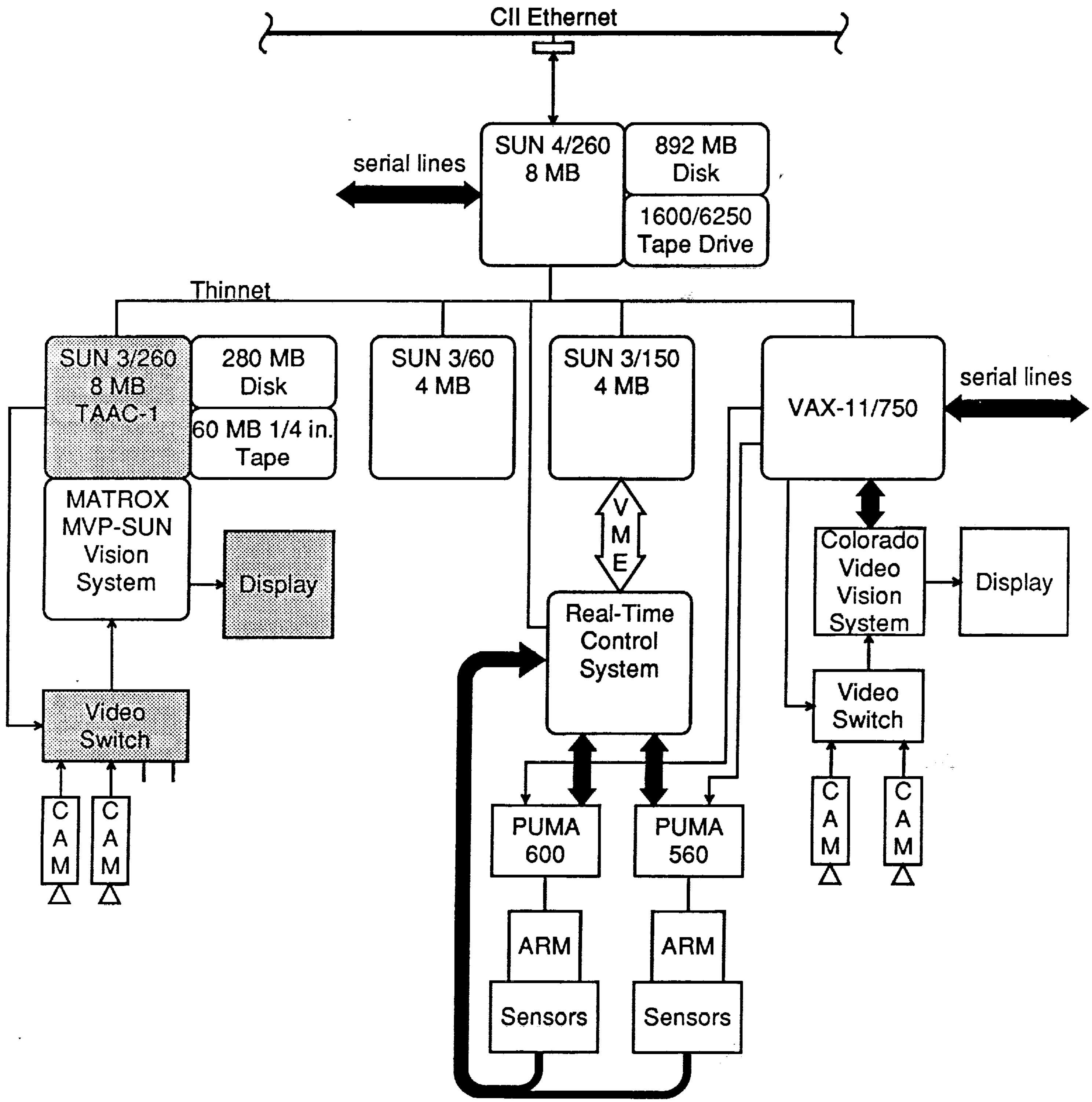

FIGURE H.4 NASA Lab Configuration

III. FACULTY, STUDENTS AND STAFF

A. FACULTY

George N. Saridis, Professor of Electrical, Computer and Systems Engineering and Director of CIRSSE; intelligent control systems, pattern recognition, computer systems, robotics, prostheses.

Stephen J. Derby, Associate Professor of Mechanical Engineering, Aeronautical Engineering and Mechanics; mechanisms, kinematics and robotics, computer graphics, design.

Alan A. Desrochers, Associate Professor of Electrical, Computer and Systems Engineering; nonlinear systems, robotics, control of automated manufacturing systems.

Lester A. Gerhardt, Professor of Electrical, Computer and Systems Engineering and Computer Science; communication systems, sensor technology and integration, interactive computer graphics, digital voice and image processing, adaptive systems, pattern recognition and computer integrated manufacturing.

Howard Kaufman, Professor of Electrical, Computer and Systems Engineering; digital control systems, adaptive systems applications and theory, optimal control.

Robert B. Kelley, Professor of Electrical, Computer and Systems Engineering; robotic systems, machine intelligence, machine vision, expert systems.

L. Kenneth Lauderbaugh, Assistant Professor of Mechanical Engineering, Aeronautical Engineering and Mechanics; automatic control, manufacturing.

Arthur C. Sanderson, Professor and Chairman of Electrical, Computer and Systems Engineering; robotics, knowledge-based systems, computer vision.

C.N. Shen, Active Professor Emeritus of Electrical, Computer and Systems Engineering; navigation of mobile robots, laser ranging systems.

John T. Wen, Assistant Professor of Electrical, Computer and Systems Engineering; multiple-arm manipulation and control, distributed parameter systems.

B. STUDENTS

1. Graduate Students

- C.H. Chung
- Tony DeLaRosa
- David Gatlin
- Kostas Kyriakopoulos
- Rajive Mathur
- John McInroy
- Fred Miller
- Scott Miller
- Michael Mittman
- Michael Moed
- Davetta Montgomery
- Steve Murphy
- Greg Neat
- B. Ravichandran
- Vincent Ree
- Mike Repko
- Jane Robinson
- Elizabeth Simpson
- Deepak Sood
- Jay Sullivan
- Glenn Tarbox
- Sharon Tocker
- Efstratios Varkaris
- Feiyue Wang
- Henry Welch
- Hui Zhang
- Edward Zucker

2. Undergraduate Students

- Linden Carmichael
- Yoon Yung Lee
- Kenneth Singletary

C. ADMINISTRATIVE AND TECHNICAL STAFF

Judi Bloomingdale is the administrative assistant and secretary to the Center and the technical staff is composed of Ken Walter, research engineer and a software engineer will be hired in the near future.

IV. NASA VISITS

A. ON-CAMPUS VISITS

1. October 31, 1988 - Charlie Schutz, Deputy Director and Julio Varsi of Jet Propulsion Laboratory
2. November 10, 1988 - B. Balaram, M. Dahlgren, K. Kreutz and G. Rodriguez of Jet Propulsion Laboratory.
3. November 18, 1988 - Chuck Fueschel, David Provost, Lloyd Purvis and Bill Tumulty of Goddard Space Flight Center.

B. OFF-CAMPUS VISITS

1. June 2, 1988 - L.K. Lauderbaugh and G.N. Saridis visited Goddard Space Flight Center.
2. August 16-18, 1988 - A.C. Sanderson and G.N. Saridis visited Jet Propulsion Laboratory.
3. November 1, 1988 - H. Kaufman visited Jet Propulsion Laboratory.
3. December 6-7, 1988 - G.N. Saridis attended INSTEP'88 in Atlanta, Georgia as a Panel Member.
4. December 12-13, 1988 - A.C. Sanderson visited Jet Propulsion Laboratory.
5. January 27, 1989 - A.A. Desrochers, R.B. Kelley and L.K. Lauderbaugh will visit Goddard Space Flight Center.
6. January 31-February 2, 1989 - A.A. Desrochers, R.B. Kelley, M.C. Moed, A.C. Sanderson, G.N. Saridis and J. Wen will visit Jet Propulsion Laboratory for the NASA Conference on Space Telerobotics.

V. PUBLICATIONS

A. JOURNAL ARTICLES

1. Desrochers, A.A., "Modeling of Nonlinear Discrete Time Systems from Input-Output Data", Automatica, Vol. 24, No. 5, September 1988, pp. 631-645 (H. Diaz and A.A. Desrochers).

2. Desrochers, A.A., "Motion Control", invited article for the Encyclopedia of Robotics, John Wiley & Sons, Inc., 1988, pp. 943-963.

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4. Gerhardt, L.A. (Chair-Major Author) et al., Robotics for Air Force Operations, National Academy Press, December 1988.

5. Gerhardt, L.A., C. Malloch and W. Kwak, "A Class of Adaptive Model and Object Driven Nonuniform Sampling Methods for 3-D Inspection", Journal for Machine Vision and Applications, 1988.

6. Gerhardt, L. and S. Park, "Autoregressive Spectral Estimation", IEEE Transactions Acoustics, Speech and Signal Processing, December 1988.

7. Peshkin, M.A. and A.C. Sanderson, "Planning Robotic Manipulation Strategies for Work Pieces that Slide", IEEE Journal of Robotics and Automation, Vol. 4, No. 5, October 1988, pp. 524-531.

8. Peshkin, M.A. and A.C. Sanderson, "The Motion of a Pushed, Sliding Work Piece", IEEE Journal of Robotics and Automation, Vol. 4, No. 6, December 1988, pp. 569-598.

9. Peshkin, M.A. and A.C. Sanderson, "Minimization of Energy in Quasi Static Manipulation", Proceedings of 1988 IEEE International Conference on Robotics and Automation, pp. 421-426.

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11. Saridis, G.N., "Entropy Formulation of Optimal and Adaptive Control", IEEE Transactions on Automatic Control, Vol. 33, No. 8, August 1988.

12. Saridis, G.N., "Knowledge Implementation: Structures of Intelligent Control Systems", Journal of Robotics Systems, J. Wiley & Sons, Vol. 5, No. 4, pp. 255-268, 1988.

13. Saridis, G.N., "An Analytic Formulation of Knowledge Based Systems for Intelligent Machines", G.N. Saridis and H. Stephanou eds., NATO Series, Springer Verlag, 1989.

14. Valavanis, K.P. and G.N. Saridis, "Architectural Models for Intelligent Robotic Systems", Advances in Automation and Robotics, Vol. 2, JAI Press, Greenwich, CT, December 1988.

15. Wen, J.T. and A.A. Desrochers, "An Algorithm for Obtaining Bang-Bang Control Laws", Jet Propulsion Laboratory New Technology Report, JPL I.R. 30-D-17603/7107, August 16, 1988, 17 pp.

B. CONFERENCE PROCEEDINGS

1. Al-Jaar, R.Y. and A.A. Desrochers, "A Survey of Petri Nets in Automated Manufacturing Systems", Proceedings of the 12th IMACS World Congress on Scientific Computation, July 18-22, 1988, Paris, France.

2. Al-Jaar, R.Y., A.A. Desrochers and F. DiCesare, "Evaluating Part-Type Mix for a Machining Workstation Using Stochastic Petri Nets", Proceedings of the 27th IEEE Conference on Decision and Control, December 1988, Austin, TX.

3. Bonner, S. and R.B. Kelley, "A Representation Scheme for Rapid 3-D Collision Detection", Proceedings of the Third International Symposium on Intelligent Control, Washington, D.C., August 1988 (in press).

4. Chen, Y. and A.A. Desrochers, "A Minimum-Time Control Algorithm for Robotic Manipulators with Point-to-Point Motion", Proceedings of the IEEE 1988 International Conference on Systems, Man, and Cybernetics, Beijing, China, August 1988.

5. Homem de Mello, L.S. and A.C. Sanderson, "Planning Repair Sequences Using the AND/OR Graph Representation of Assembly Plans", Proceedings of 1988 IEEE International Conference on Robotics and Automation, pp. 1861-1863.

6. Homem de Mello, L.S. and A.C. Sanderson, "Task Sequence Planning for Assembly", Proceedings of 12th Annual IMACS World Congress, July 1988.

7. Homem de Mello, L.S. and A.C. Sanderson, "Task Sequence Planning for Assembly", 12th IMACS World Congress, Paris, France, July 1988.

8. Kelley, R.B., "2D Vision Techniques for the Handling of Limp Materials", Sensor-Based Robots: Algorithms and Architectures, NATO Adv. Res. Workshop, Barga, Italy, October 1988 (in press).

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13. Sanderson, A.C., "Panel Discussion on Intelligent Control Systems", 1988 IEEE International Symposium on Intelligent Control, Washington, D.C., August 26, 1988.

14. Sanderson, A.C. and L.S. Homem de Mello, "Representation Issues in Assembly Sequence Planning", 1988 IFIP/NSF Workshop on Geometric Modeling, Rensselaerville, NY, September 18-22, 1988.

15. Sanderson, A.C. and L.S. Homem de Mello, "Real-Time Planning and Intelligent Control", 1988 NATO Advanced Research Workshop on Knowledge-Based Robot Control, Bonas, France, October 10-12, 1988.

16. Sanderson, A.C., "Applications of Neural Networks to Robotics", 1988 NSF Workshop on Neural Control: Problems and Opportunities, Portsmith, NH, October 16-18, 1988.

17. Sanderson, A.C. and L.S. Homem de Mello, "Evaluation Functions for Assembly Sequence Planning", 1988 SPIE Cambridge Symposium on Space Robotics, Cambridge, MA, November 8-10, 1988.

18. Sanderson, A.C. and L.S. Homem de Mello, "Evaluation Functions for Assembly Sequence Planning", *Proceedings of 1988 SPIE Cambridge Symposium on Space Robotics*, November 1988.

19. Sanderson, A.C. and L.S. Homem de Mello, "Representation Issues in Assembly Sequence Planning", *Proceedings of 1988 IFIP/NSF Workshop on Geometric Modeling* (in press).

20. Sanderson, A.C. and L.S. Homem de Mello, "Real-Time Planning and Intelligent Control", *Proceedings of NATO Advanced Research Workshop on Knowledge-Based Robot Control* (in press).

21. Sanderson, A.C., "Applications of Neural Networks in Robotics", *Proceedings of NSF Workshop on Neural Control: Problems and Opportunities* (in press).

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23. Saridis, G.N., "Analytic Formulation of the Principle of Increasing Precision with Decreasing Intelligence for Intelligent Machines", the *IFAC 1988 SYROCO Conference*, Karlsruhe, W. Germany, October 1988.

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25. Saridis, G.N., "On the Theory of Intelligent Machines - A Survey", *Proceedings of Conference on Decision and Control*, Austin, TX, December 1988.

26. Sood, D., M. Repko, M.C. Moed and R.B. Kelley, "A Fuzzy Approach to the Interpretation of Robot Assembly Forces", Proceedings of the SPIE Symposium: Intelligent Robots and Computer Vision, Cambridge, MA, November 1988 (in press).

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30. Wen, J.T. and K. Kreutz, "A Control Perspective for Multiple-Arm Systems", International Symposium. on Robotics, Albuquerque, NM, November 1988.

31. Wen, J.T. and K. Kreutz, "Stability Analysis of Multiple Rigid Robot Manipulation Holding a Common Rigid Object", IEEE Decision and Control Conference, Austin, TX, 1988.

32. Wen, J.T. and K. Kreutz, "Globally Stable Control Laws for the Attitude Control Problem: Tracking Control and Adaptive Control", IEEE Decision and Control Conference, Austin, TX, 1988.

33. Wen, J.T., "Controller Synthesis for Infinite Dimensional Systems Based on a Passivity Approach", IEEE Decision and Control Conference, Austin, TX, 1988.

C. BOOKS

1. Desrochers, A.A., Modeling and Control of Automated Manufacturing Systems, a tutorial text under contract with the IEEE Computer Society Press, expected publication date, Spring 1989.

2. Saridis, G.N., Editor, Advances in Automation and Robotics, Vol. 2, JAI Press, December 1988.

3. Saridis, G.N., Editor, "Knowledge Based Systems for Intelligent Machines" with H. Stephanou, Springer Verlag (NATO ASI Senses) Spring 1989.

D. CIRSSE REPORTS

1. Saridis, G.N. and M.C. Moed, "Analytic Formulation of Intelligent Machines as Neural Nets", October 1988.

2. Saridis, G.N., "Intelligent Machines: Distributed versus Hierarchical Intelligence", October 1988.

3. Saridis, G.N., "An Analytic Formulation of Knowledge-Based Systems for Intelligent Machines, October 1988.

4. McInroy, J.E. and G.N. Saridis, "Acceleration and Torque Feedback for Robotic Control: Experimental and Theoretical Results", November 1988.

5. Saridis, G.N., "Analytic Formulation of the Principle of Increasing Precision with Decreasing Intelligence for Intelligent Machines", October 1988.

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9. Kelley, R.B. and S. Bonner, "A Representation Scheme for Rapid 3-D Collision Detection", August 1988.

10. Ree, V.J., Jr. and L.K. Lauderbaugh, "Issues in the Safety of Complex Systems", November 1988.

11. Chen, Y., "Minimum-Time Control of Robotic Manipulators", August 1988.

12. Chung, C.H. and G.N. Saridis, "Obstacle Avoidance Path Planning by the Extended VGraph Algorithm", January 1989.

13. Wen, J.T., "Robustness Analysis for Evolution Systems in Hilbert Space: A Passivity Approach, December 1988.